US006389045B1

(12) United States Patent
Mann et al.

(10) Patent No.: US 6,389,045 B1
(45) Date of Patent: May 14, 2002

(54) OPTICAL PULSE STRETCHING AND SMOOTHING FOR ARF AND F_2 LITHOGRAPHY EXCIMER LASERS

(75) Inventors: **Klaus Mann**; **Thomas Schröder**, both of Göttingen; **Bernd Schäfer**, Goslar; **Uwe Leinhos**; **Uwe Stamm**, both of Göttingen, all of (DE)

(73) Assignee: **Lambda Physik AG**, Goettingen (DE)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/550,558**

(22) Filed: **Apr. 17, 2000**

Related U.S. Application Data

(60) Provisional application No. 60/130,392, filed on Apr. 19, 1999.

(51) **Int. Cl.**[7] **H01S 3/10**

(52) **U.S. Cl.** 372/25; 372/700; 372/100; 372/98; 372/93; 372/20

(58) **Field of Search** 372/25, 100, 98, 372/93, 20, 706

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,390,247	A	*	6/1983	Freyre	372/700
4,866,721	A		9/1989	Aoshima et al.	372/30
4,901,323	A		2/1990	Hawkins et al.	372/25
4,928,316	A		5/1990	Heritage et al.	455/600
5,210,807	A		5/1993	Ames et al.	385/24
5,309,456	A		5/1994	Horton	372/25
5,317,577	A	*	5/1994	Urakami et al.	372/700
5,329,398	A		7/1994	Lai et al.	359/566
5,337,333	A	*	8/1994	Daly et al.	372/700
5,349,591	A		9/1994	Weston et al.	372/25
5,475,525	A	*	12/1995	Tournois et al.	372/700
5,513,194	A		4/1996	Tamura et al.	372/6
5,617,434	A		4/1997	Tamura et al.	372/6
5,671,241	A	*	9/1997	Stamm et al.	372/700
5,786,888	A		7/1998	Allen et al.	356/73
5,847,863	A	*	12/1998	Galvanausky et al.	359/341
6,067,311	A		5/2000	Morton et al.	372/57
6,314,119	B1	*	11/2001	Morton	372/25

FOREIGN PATENT DOCUMENTS

EP	0 552 093 A1	1/1993	
EP	0 984 531 A2	3/2000	H01S/3/00
JP	4-73983	3/1992	
JP	4-147683	5/1992	
JP	6-214187	8/1994	
RU	1140091 A	2/1985	

OTHER PUBLICATIONS

W.R. Callen, et al., "Pulse Stretching of Q-Switched Lasers," *Opto-Electronics*, vol. 1, No. 1, Feb. 1969, pp. 123–127.

D. C. Hamilton, "Pulse Stretching with C0 in a Tea $C0_2$ Laser" *Optics Communications*, vol. 19, No. 3, Dec. 1976, pp. 339–342.

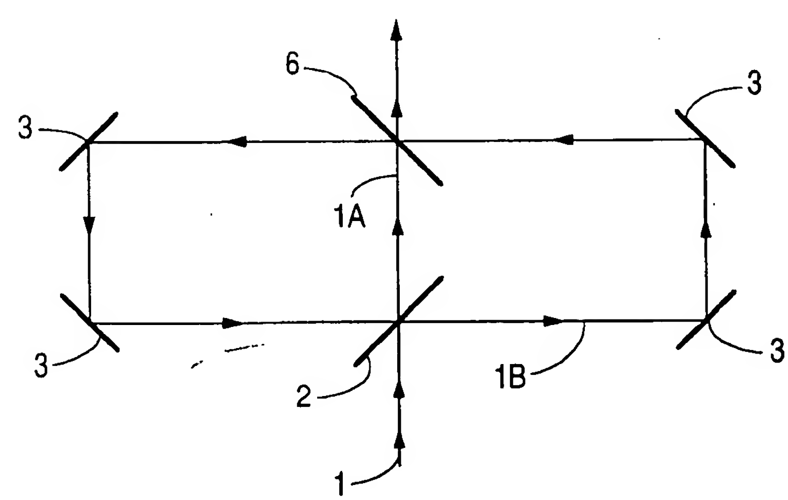
(List continued on next page.)

Primary Examiner—Leon Scott, Jr.
(74) *Attorney, Agent, or Firm*—Sierra Patent Group, Ltd.; Andrew V. Smith

(57) **ABSTRACT**

A method and apparatus are provided for temporally stretching and smoothing of the pulses of an output beam of excimer and lithography lasers. The method and apparatus are based upon providing an optical delay line or circuit having a plurality of optical reflectors and a plurality of beam recombiners or splitters so arranged as to divide the pulse into numerous portions which vary in their travel time through the circuit. As a result, the energy of the incident pulse is greatly stretched and smoothed.

39 Claims, 3 Drawing Sheets



the laser pulse. By this method, the maximum peak intensity can be substantially reduced and pulse stretching of more than a factor of 2 can easily be achieved.

Another advantage of this arrangement is that all light portions propagate only in the direction of the delay line output, no light is referenced back. Therefore, high transmission values of the delay line are achievable. Further, placement of a second partially reflective mirror (6) in the optic delay circuit corrects for the refraction associated with each passage through the first partially reflective mirror (2).

To achieve high transmission of the delay line in the deep UV spectral range the whole system is tightened and flushed with nitrogen or any other non-reacting gas that does not show any light absorption in the spectral range between 150 and 200 nm. Alternatively, when it is desired to reduce gas absorption of light energy, the whole delay line can also be evacuated.

There are two additional methods to achieve high prolongation factors (>2). One method is to realize a long delay line with either large geometrical dimensions or many optical components for beam folding. The disadvantage with both methods stems from the great difficulty in achieving a high optical stability for the whole system. On the other hand, using cascaded delay lines (i.e., delay lines where a light portion undergoes direction reversals and multiply encounters an optical element prior to completing a full circuit) or multiple passes through a single delay line as in FIG. 5 can allow for very large extension values (>2 or 3) without a corresponding increase in geometry. An advantage of cascaded delay lines is that each single delay line of a cascaded set-up has small geometrical dimensions and the whole delay setup is modular, i.e., the user can combine as much delay lines as it is necessary for his application. The disadvantage is, that in special cases quite a lot of optical components are necessary.

As indicated by the light paths in FIG. 5, portions of the incident light beam which are reflected at any of the four encounters with a beam splitter are reflected into the optical delay circuit. An incident light beam must first be transmitted through a first beam splitter (15), a second beam splitter (16), and then after being reflected by a prism (14) be retransmitted a second time through both the second (16) and first (15) beam splitters. Thus, an incident light beam has four opportunities to be reflected into the optical delay circuit before exiting the device. Assuming 50% reflection/transmission at each optical reflector/beam splitter, approximately only $\frac{1}{16}^{th}$ of the incident light beam passes through without some delay due to diversion into the optical delay circuit.

Each additional interaction with a beam splitter greatly increases the likelihood that some portions of the incident beam which were reflected into the optical delay circuit will be retained in the circuit for a greater travel distance, and therefore a longer period of time. For example, the portion of an incident beam which was initially reflected at the first beam splitter, will travel from the first minor prism (11) to the major prism (13) to a second minor prism (12) and then to the second beam splitter (16). If a portion of this beam is to directly proceed from this point to the exit point from the optical delay device, it must first be reflected by the second beam splitter (16), whereupon it is reflected by the return prism (14) to the second beam splitter (16) again where upon it must be transmitted through both the second beam splitter (16) and the first beam splitter (15). Only one-eight of the initially reflected beam (or one-sixteenth of the incident light beam) will therefore follow this most direct route to exit the optical delay circuit.

To achieve the same beam properties of the laser beam after each round trip imaging optics can be introduced into the delay line. FIG. 6 illustrates the use of optical lenses to correct for beam distortions involved in the transit of light through the optical delay circuits. The imaging optics may be coated with anti-reflective materials. The imaging optics can also be finely adjustable to shape and tune the temporal profile of said pulse. Thus, any beam distortions due to the high divergence of excimer laser radiation can be corrected.

The Time Integral Square:

$$TIS = \frac{\left[\int I(t)dt\right]^2}{\int I^2(t)dt} \quad \begin{array}{l} I(t) - \text{Intensity of the light} \\ t - \text{time} \end{array}$$

provides a measure of how much a laser pulse has been stretched out over time. This measure is therefore useful in evaluating the performance of optical delay systems. FIG. 7 shows the initial 30 ns of an unstretched excimer laser pulse and the stretched pulse after having passed a delay line with a round trip delay of 6 ns. In this case, the Time Integral Square could be increased by a factor of only 1.63. FIG. 8 show the pulse stretching after 2 cascaded delay lines with 6 ns delay time in each delay line. The TIS is now prolonged by a factor of 2.14. In FIG. 9 the original and the stretched pulse after 2 cascaded delay lines with 12 ns delay time in each delay line is shown. The TIS was prolonged by a factor of 2.76. The substantial TIS factors which are obtained with these methods are capable of substantially prolonging the life of optical materials, such as those used in microlithography, whose photodegradation is especially aggravated by the peak intensity of a light pulse.

Those skilled in the art will appreciate that the just disclosed preferred embodiments are subject to numerous adaptations and modifications without departing from the scope and spirit of the invention. For instance, dielectric mirrors may be used to direct or split the incident laser light. The reflectivity of the mirrors of the optical circuit may be varied from 5% to 95%. The length of the delay lines can be finely adjusted to smooth out the intensity spikes. The optical elements may be made of a variety of suitable materials including calcium flouride (CaF_2), fused silica, sapphire, barium flouride (BaF_2) and magnesium fluoride (MgF_2).

Therefore, it is to be understood that, within the scope and spirit of the invention, the invention may be practiced other than as specifically described above. The scope of the invention is thus not limited by the particular embodiments described above. Instead, the scope of the present invention is understood to encompass the claims that follow, and structural and functional equivalents thereof.

We claim:

1. An optical pulse stretcher, comprising a plurality of optical beam splitters for dividing a laser pulse into multiple beam portions including multiple delayed beam portions, a plurality of optical reflectors configured with said optical beam spliters so as to provide an optical delay circuit characterized by a plurality of reflections and a plurality of different optical path lengths for said delayed beam portions to travel; and wherein said beam splitters and optical reflectors direct said beam portions into, around, or out of, said circuit, and wherein said laser pulse is stretched and thereby a peak intensity of said laser pulse is reduced such as to substantially reduce damage to optical materials in the beam path after the pulse stretcher.

2. An optical pulse stretcher of claim 1, wherein said circuit comprises a first beam splitter and a second beam

splitter each separately positioned to intercept a portion of said pulse traveling on said shortest route through said stretcher and a portion of said pulse traveling across said route; and wherein said first beam splitter and said second beam splitter are oriented so as to divert a portion of said pulses traveling on said route off of said route and to divert a portion of said pulse traveling across said route onto said route.

3. An optical pulse stretcher of claim 1, wherein said optical delay circuit comprises a first beam splitter and a second beam splitter wherein refraction of a portion of said pulse transmitted through said first beam splitter is corrected by transmission of said portion through said second beam splitter.

4. An optical pulse stretcher according to claim 1, wherein said circuit is under a vacuum or under an atmosphere which minimally absorbs pulse energies between 200 nm and 150 nm.

5. An optical pulse stretcher according to claim 1, wherein said optical reflectors comprise prisms using total internal reflection.

6. An optical pulse stretcher according to claim 5, wherein said prisms are made of one from the group consisting of CaF_2, fused silica, sapphire, MgF_2 and BaF_2.

7. An optical pulse stretcher according to claim 5, wherein said prisms are anti-reflection coated.

8. An optical pulse stretcher according to claim 1, wherein said optical beam splitters are partially reflective surfaces.

9. An optical pulse stretcher according to claim 1, wherein said optical reflectors comprise highly reflective mirrors.

10. An optical pulse stretcher according to claim 1, wherein said beam splitters are a plurality of dielectric mirrors with a reflectivity between 5% and 95%.

11. An optical pulse stretcher according to claim 1, wherein said beam splitters are a plurality of dielectric mirrors with a reflectivity of about 50%.

12. An optical pulse stretcher according to claim 1, wherein said beam splitters are made from one of the group consisting of CaF_2, fused silica, sapphire, MgF_2 and BaF_2.

13. An optical pulse stretcher according to claim 1, wherein said circuit is comprised of delay lines whose lengths may be finely adjusted to smooth out intensity spikes.

14. An optical pulse stretcher according to claim 1, wherein said circuit is comprised of cascaded paths for said portions to travel.

15. An optical pulse stretcher according to claim 1, wherein said circuit is comprised of imaging optics to correct distortion of said pulse due to passage of said pulse through said circuit.

16. An optical pulse stretcher according to claim 15, wherein said imaging optics are finely adjustable to shape and tune the profile of said pulse.

17. An optical pulse stretcher as in claim 15, wherein elements of said imaging optics are made from one of the group consisting of CaF_2, fused silica, sapphire, MgF_2 and BaF_2.

18. An optical pulse stretcher as in claim 15, where elements of said imaging optics are anti-reflection coated.

19. An optical pulse stretcher, comprising:

a) a first beam splitter located in the path of said pulse for transmitting a first portion of an output pulse and reflecting a second portion of said pulse;

b) a plurality of optical reflectors positioned to redirect said second portion along a route which intersects said first portion and thereafter intersects said first beam splitter; and

c) a second beam splitter located at the point where said route intersects with said path of said first portion; wherein said second beam splitter is oriented to reflect a portion of said second portion in a manner to recombine said reflected second portion with a portion of said first portion which is transmitted by said second beam splitter, said second beam splitter also functioning to transmit a portion of said second portion and reflect a portion of said first portion in a manner to recombine said transmitted portion of said second portion and said reflected portion of said first portion, and

wherein said output pulse is stretched and thereby its peak intensity is reduced such as to substantially reduce damage to optical materials in the beam path after the pulse stretcher.

20. A pulse stretcher as recited in claim 19, wherein there are four optical reflectors positioned at the corners of a rectangle.

21. A pulse stretcher as recited in claim 19, wherein said optical reflectors comprise prisms.

22. An optical pulse stretcher according to claim 21, wherein said route is cascaded so as to reduce the overlap in said prisms of the energy of said portions undergoing multiple passes.

23. A pulse stretcher as recited in claim 21, wherein there are two prism reflectors.

24. An optical pulse stretcher according to claim 21, wherein said prisms are made of one from the group consisting of CaF_2, fused silica, sapphire, MgF_2 and BaF_2.

25. An optical pulse stretcher according to claim 21, wherein said prisms are anti-reflection coated.

26. An optical pulse stretcher according to claim 19, wherein said optical beam splitters comprise partially reflective surfaces.

27. An optical pulse stretcher according to claim 26, wherein said beam splitters are a plurality of dielectric mirrors with a reflectivity between 5% and 95%.

28. An optical pulse stretcher according to claim 26, wherein said beam splitters are a plurality of dielectric mirrors with a reflectivity of about 50%.

29. An optical pulse stretcher according to claim 19; wherein the proportion of the energy of said pulse traveling said route and the times of traveling along said route are sufficient to increase the time integral square of said pulse by a factor of 1.5.

30. An optical pulse stretcher according to claim 19, wherein said route is of sufficient length that a portion of said pulse can not travel it in less than 4 seconds.

31. An optical pulse stretcher according to claim 19, wherein said beam splitters are made from one of the group consisting of CaF_2, fused silica, sapphire, MgF_2 and BaF_2.

32. An optical pulse stretcher according to claim 19, comprising imaging optics to correct divergence of said pulse occurring on said route.

33. An optical pulse stretcher according to claim 32, wherein said imaging optics are finely adjustable to shape and tune the profile of said pulse.

34. An optical pulse stretcher as in claim 32, wherein elements of said imaging optics are made from one of the group consisting of CaF_2, fused silica, sapphire, MgF_2 and BaF_2.

35. An optical pulse stretcher as in claim 32, where elements of said imaging optics are anti-reflection coated.

36. An optical pulse stretcher according to claim 19, wherein said route is under a vacuum or under an atmo-

sphere which minimally absorbs pulse energies between 200 nm and 150 nm.

37. An optical pulse stretcher, comprising:

a) a first beam splitter located in the path of said pulse for transmitting a first portion of an output pulse and reflecting a second portion of said pulse;

b) a second beam splitter located in the path of said pulse for transmitting a portion of said pulse and reflecting a third portion of said pulse;

c) a plurality of prisms positioned to delay said second portion and said third portion different amounts by passage along a cascaded route which increases the amount of said delay for a given prism spacing; and

d) a means of recombining said second portion and said third portion with said first portion, and

wherein said output pulse is stretched and thereby its peak intensity is reduced such as to substantially reduce damage to optical materials in the beam path after the pulse stretcher.

38. An optical pulse spreader as in claim 37, wherein said means of recombining comprises a second beam splitter located at the point where said route intersects with said path of said first portion; wherein said second beam splitter is oriented to reflect a portion of said second portion in a manner to recombine said reflected second portion with a portion of said first portion which is transmitted by said second beam splitter, said second beam splitter also functioning to transmit a portion of said second portion and reflect a portion of said first portion in a manner to recombine said transmitted portion of said second portion and said reflected portion of said first portion.

39. An optical pulse stretcher of claim 37, wherein said stretcher has a modular configuration which allows said stretcher to be combined in series with another of said stretcher; said series combination stretching said pulse to a greater extent than the stretching provided by one of said stretcher.

* * * * *